Puget Sound's Eelgrass Meadows: Factors Contributing to Depth Distribution and Spatial Patchiness

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Introduction

The purpose of the present paper is to examine light requirements of eelgrass (*Zostera marina* L.) and discuss factors leading to eelgrass distribution and patchiness using a large data set on depth distribution in Puget Sound. Eelgrass is a rooted flowering plant that forms meadows in the shallow waters of Puget Sound. It is the most widely distributed species of seagrass in the temperate areas of the Northern Hemisphere (Phillips and Menez 1988; Wyllie-Echeveria and Thom 1994). Over the past 20 years, scientists, regulators, and the public have become increasingly aware of the importance of eelgrass meadows to the Puget Sound nearshore ecosystems. Eelgrass forms habitat for a diverse assemblage of animals, including Dungeness crab, juvenile salmon, and herring (Phillips 1984).

Multiple environmental factors interact to control the distribution of eelgrass, including light, substrata type, salinity, and wave action. Simple biophysical models are now being developed that predict both the presence and, to a lesser degree, the abundance of eelgrass, based on an understanding of the relationship between the controlling factors and eelgrass requirements.

Pollutant discharges to marine waters and coastal development projects place constant pressure on healthy and viable eelgrass meadows. Studies we have been conducting over the past four years have revealed large areas in Puget Sound where environmental conditions appear to be favorable for eelgrass, but where eelgrass is not present or in very low abundance. We have been able to explain some of this variability as effects of past or present disturbances at these sites. For example, eutrophication, shading, propeller wash, and disturbance by foraging crabs have been documented to cause fragmentation of existing meadows (Thom et al. 1988; Simenstad et al. 1997). Recovery of these areas may be limited by some other environmental factors.

Light is of paramount importance in determining the distribution of eelgrass (Olson and Thom 1997). Over the past four years, there has been a growing research effort to understand the effects of shading from overwater structures on eelgrass (Simenstad et al. 1997). Models are currently being developed to help predict the effects of proposed structures on the distribution of eelgrass (e.g., Olson et al. 1997). We have developed eelgrass cover maps and a large data set on eelgrass depth and density through studies conducted near ferry terminals for the Washington State Department of Transportation (WSDOT). These data allow us to draw some general conclusions about the effects of light availability and quality on depth distribution and about factors contributing to the spatial patchiness of eelgrass in Puget Sound.

Study Sites

The field studies were conducted near the following seven Washington State Ferry terminals that span north and central Puget Sound: Anacortes, Port Townsend, Clinton, Kingston, Edmonds, Southworth, and Vashon Island (Figure 1). Controlled productivity-irradiance studies were conducted in outdoor flowing seawater tanks at Battelle Marine Sciences Laboratory located at the mouth of Sequim Bay.

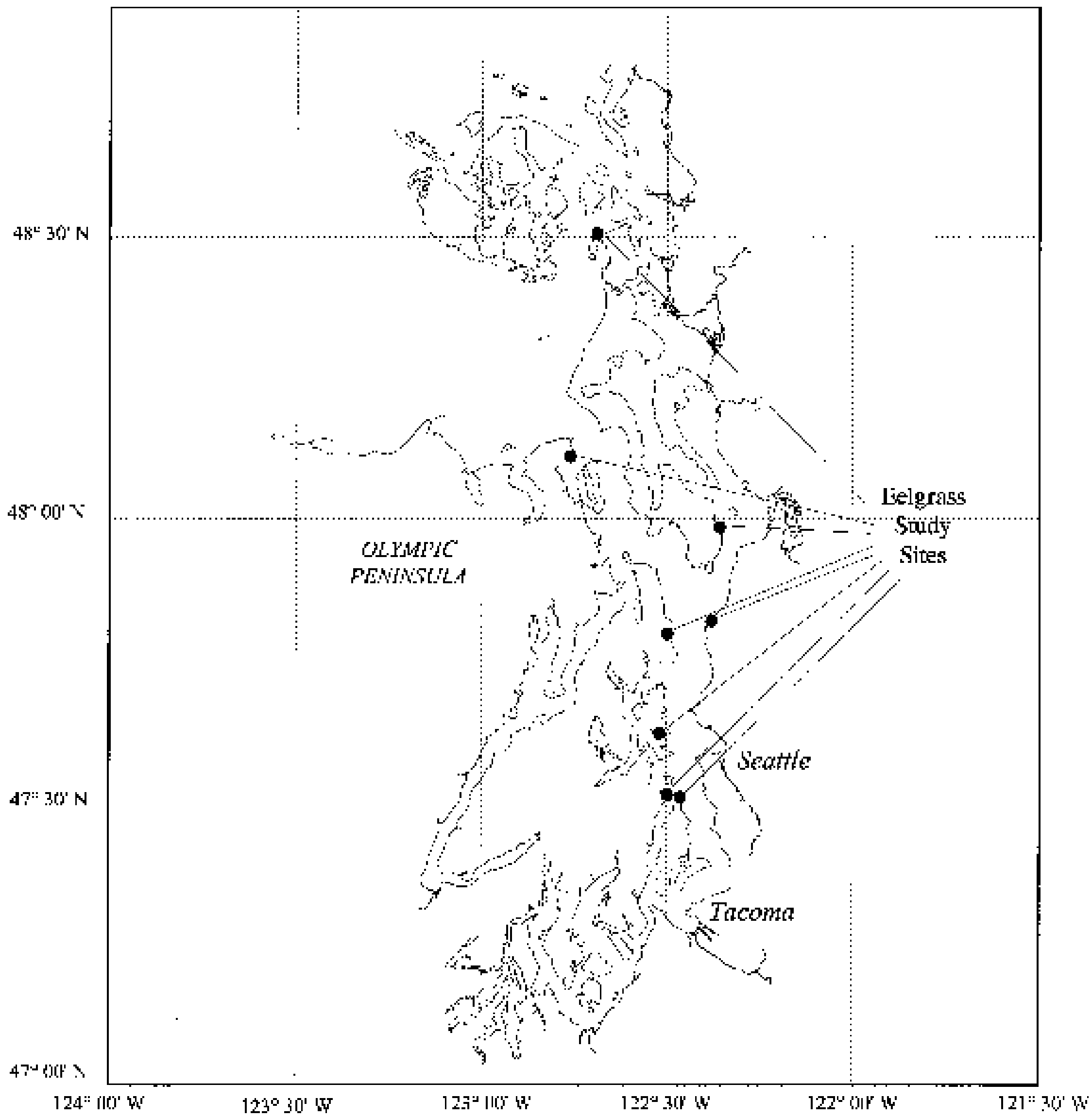

Figure 1. Location of eelgrass study sites in Puget Sound, Washington.

Methods

Eelgrass Mapping and Density Measurements

We employed video survey techniques (Norris et al. 1997), aerial photographs, and systematic diver surveys to accurately map eelgrass at the seven terminals (Thom et al. 1997). Divers ground-truthed the aerial photographs by sampling eelgrass density within triplicate 0.25-m^2 quadrats placed at 5- to 10-m intervals along transects. Depths measured by divers were calibrated to predicted tides each day. In total, the surveys produced 1,348 density-depth measurements.

In addition to density measurements, divers recorded any factors that might affect the abundance of eelgrass such as animals, propeller wash, and anchors chains at the seven terminals. At most sites, divers also noted the presence of seaweeds in the quadrats, in particular *Ulva* spp. To partially test the relationship between *Ulva* and eelgrass, we performed a 2 x 4 χ^2 test on data from one of the sites (Southworth) that showed an observable *Ulva*-eelgrass interaction. The test evaluated the observed frequency of *Ulva* relative to the expected frequency of *Ulva* within four eelgrass cover classes using the 212 observations from the site.

Net Productivity-Irradiance (P-I) Experiments

Over the period of 1991 to 1994, the relationship between eelgrass photosynthesis and level of photosynthetically active radiation (PAR) was experimentally determined using short-term (i.e., 2-hr) incubations of leaf sections (Simenstad et al. 1997). Leaf sections were placed in 1-L bottles filled with seawater and incubated under ambient PAR and sea temperature. Experiments were conducted several times during winter, spring, and summer. Five replicate bottles containing eelgrass along with five replicate water-only controls were incubated during each experiment. Ambient PAR was recorded continuously during each experiment using a Licor quantum sensor.

Light Attenuation

In August 1997 and February 1998, we measured PAR profiles by depth at five sites in Eagle Harbor, Washington. The sites ranged from relatively quiescent areas in the middle portion of the Harbor where eelgrass was very sparse, to an exposed, well-flushed area (Creosote Point) where eelgrass meadows were lush. At each site, we measured PAR at 0.5-m depth intervals between the surface and the bottom using a Licor spherical quantum sensor. Measurements were made between 10 a.m. and 3 p.m. These sites are likely representative of the range of attenuation found in nearshore areas of Puget Sound; however, verification through much more widespread sampling is needed.

Results and Discussion

Eelgrass Density and Depth Measurements

The depth vs. eelgrass density data from all seven sites showed that eelgrass reaches its greatest shoot density at about -2.5 m relative to mean sea level (MSL) (Figure 2A). We use MSL here because it relates to the average depth of water over eelgrass meadows throughout the year. To convert from mean lower low water (MLLW) to MSL, we used the relationship of MLLW + 2 m Å MSL. Eelgrass was generally not found below -7 m MSL. The greatest depth at which eelgrass was found varied between -5 m and -7 m MSL. Of note is that there were numerous bare patches within the depth range for eelgrass. Also, it is worthy to note that eelgrass typically grows to a larger size with increasing depth and will naturally form beds that are less dense, but these deeper beds still maintain a high bottom cover (Thom 1990). Above about -1.0 m MSL (+1.0 m MLLW) eelgrass is limited by other stressors, the strongest of which is desiccation.

Net Productivity-Irradiance Experiments

Light controls eelgrass photosynthesis, and thereby the growth and spread of the plant. This can be demonstrated using the productivity-irradiance (P-I) curves developed in the laboratory studies. The P-I curves (Figure 3) indicate that photosynthetic rate increases rapidly up to an irradiance level of about 300 $\mu M/m^2/sec$. Although the photosynthetic rates during summer, spring, and winter all peaked at approximately the same irradiance, the peak winter rate was approximately six times greater than the summer rate. The spring rate was intermediate. Our observations indicate that the plants are narrower and greener in winter than in summer. We suggest that the plants are far more efficient at utilizing available light energy in winter, which may be due to a more efficient winter morphology. Respiration rate is also likely to be lower in winter, because of lower temperatures.

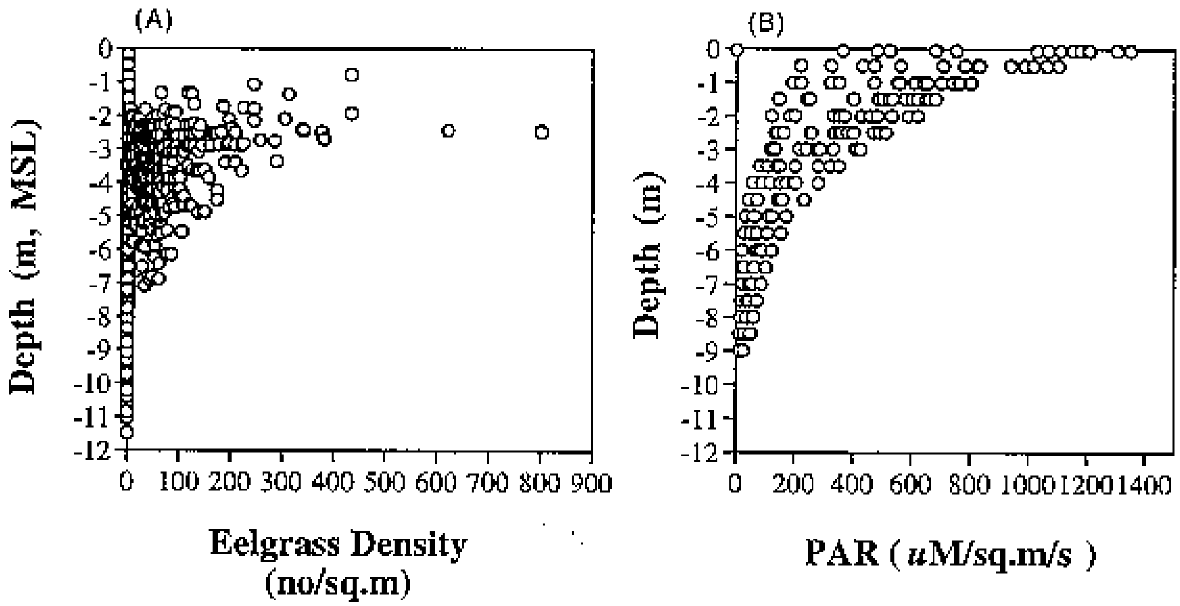

Figure 2. (A) Eelgrass shoot density vs. depth from diver sampling at the seven study sites; (B) PAR attenuation curves for sites in Eagle Harbor.

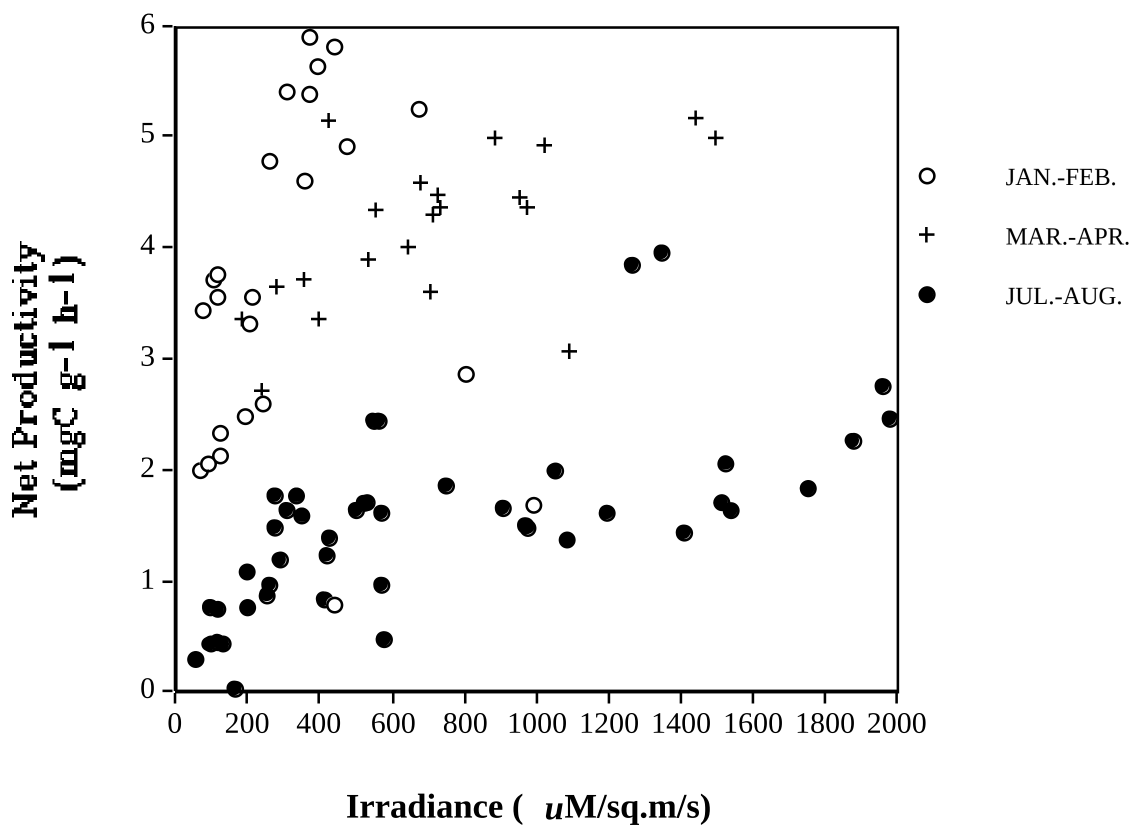

Figure 3. Net productivity vs. irradiance curves from short-term incubations of eelgrass leaf sections.

Light Attenuation

Coupled with light attenuation and eelgrass density information, the P-I curves are useful in evaluating the light requirements for eelgrass in Puget Sound. The mean light attenuation coefficient (K_d) at Eagle Harbor was 0.46 (SD = 0.13; range 0.28 to 0.80; n = 15), which is typical of many temperate estuarine systems (Kirk 1994). The attenuation curves show strong attenuation between the surface and approximately -4.5 m below the water surface, and that this corresponds with a strong decrease in maximum eelgrass density recorded at each depth (Figures 2A, 2B).

Although the attenuation curves were not collected from the sites where eelgrass was sampled quantitatively, the curves may be representative of light conditions in the northern and main basins of Puget Sound. Hence, general comparisons can be made. Maximum eelgrass shoot densities occurred where instantaneous, mid-day PAR levels were between approximately 100 and 550 $\mu M/m^2/sec$ (median Å 325 $\mu M/m^2/sec$). Lowest shoot densities occurred at PAR levels <150 $\mu M/m^2/sec$. Below about 100 $\mu M/m^2/sec$, no eelgrass was observed.

These results indicate that, on average, instantaneous mid-day PAR greater than about 150 $\mu M/m^2/sec$ is required to maintain eelgrass growth. Instantaneous PAR of approximately 325 $\mu M/m^2/sec$ is required to support maximum densities. These results are in accord with those of Simenstad et al. (1997) where long-term growth studies in flowing seawater tanks and long-term *in-situ* growth studies were used to develop light requirements for eelgrass. They also found that spring and summer were the critical periods of the year, when the plants are undergoing rapid growth, and are also storing carbohydrates in the rhizome. Carbohydrate reserves are then used to maintain the health of the plants during the fall and winter (Burke et al. 1996).

Eelgrass Mapping and Spatial Patchiness

A map of eelgrass distribution near the Vashon Island Terminal reveals the typical patchy nature of eelgrass at most of the sites (Figure 4). The loss of eelgrass at ferry terminals has been explained by Simenstad et al. (1997) as a result of historical disturbance during dock construction, shading, disturbance during maintenance operations, and propeller wash. They also noted disturbance by burrowing animals such as Dungeness crab, whose abundance was enhanced under the terminals. Areas outside the general region of the terminal were also patchy, but likely not because of terminal-associated effects.

We suggest that some of the observed fragmentation might be caused by an overabundance of seaweed biomass initiated by inorganic nitrogen loading. There is a growing awareness that *Ulva* spp. blooms occur in response to increased loading of inorganic nitrogen to nearshore systems (Short and Wyllie-Echeverria 1996). Divers reported finding a large abundance of *Ulva* spp. at virtually all sites. *Ulva* was very dense at Kingston, Vashon, and Southworth. Dense mats of *Ulva* have been shown to shade and smother eelgrass in Puget Sound (Thom et al. 1988) and New England (Short et al. 1995). In Puget Sound, impacts to eelgrass from *Ulva* have been observed in west Seattle (Thom et al. 1988), near Port Townsend (Chimacum Creek; R.M. Thom personal observation), and Seahurst Bight (Thom and Albright 1990).

Results of the 2 x 4 χ^2 test on data from Southworth indicated that there was significantly more *Ulva* present in areas with no eelgrass cover and significantly less *Ulva* present in areas with the greatest eelgrass cover (Table 1). Depth was also shown to be a factor, with more *Ulva* than expected in shallower depths and less *Ulva* than expected at deeper depths. These results allow us to at least put forth the hypothesis that there is a statistically significant negative interaction between *Ulva* and eelgrass. We believe that the hypothesis would hold for most of the sites we sampled.

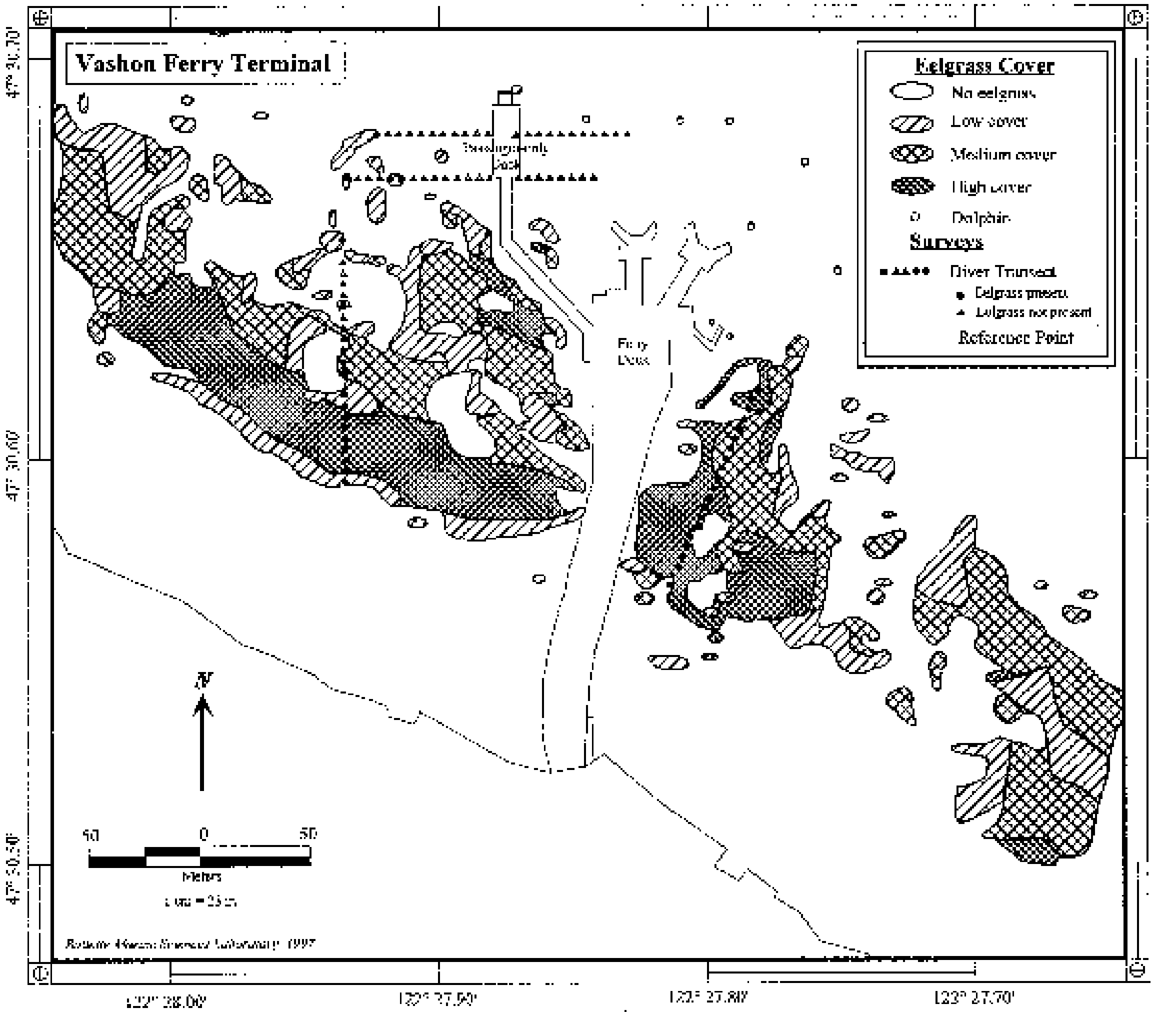

Figure 4. Map of eelgrass cover at Vashon Island ferry terminal study area (from Thom et al. 1997). Diver transects are shown, along with reference points.

Table 1. Results of analysis of the presence of *Ulva* spp. and eelgrass at sampling points at Southworth. Values are number of sampling points. Eelgrass cover is as in Figure 2.

	Eelgrass Cover				
	none	low	medium	high	total
Ulva present	116	3	3	1	123
Ulva absent	26	7	17	39	89
Total	142	10	20	40	212

Conclusions

The results of studies on light requirements provide some help in assessing impacts from proposed overwater structures on eelgrass and in determining the light level necessary to maintain eelgrass. The modeling efforts by Simenstad et al. (1997) and others will provide quantitative tools for calculating the effects of structures on eelgrass in the future. However, at present, we can say that maintaining at least 150 $\mu M/m^2/sec$ during mid-day throughout the year will likely allow eelgrass to persist. Maximum eelgrass density would require about 300 µM/m^2/sec. Based upon previous work, the critical period for light is spring and summer, when the plants build energy reserves. Simenstad et al. (1997) found that integrated daily PAR of 3 M/m^2 is required to maintain healthy populations. This means that the 300 µM/m^2/sec would have to be reaching plants for an average of about 3 hr/day.

Obviously, far more light attenuation measurements close to sites where depth and density measurements have been taken are needed to verify our findings. However, the much simpler measurement of Secchi depth (Z_{sd}) can be used to estimate attenuation (Kirk 1994), and is a key monitoring parameter in Chesapeake Bay (Batiuk et al. 1992). A simple relationship between the vertical attenuation coefficient and Secchi depth is $K_d = 1.44/ Z_{sd}$ (in Kirk 1994). Using this equation, the minimum attenuation coefficient from Eagle Harbor, 0.28 m^{-1}, yields a Secchi depth of 5.1 m. The maximum depth limit of eelgrass in our study (-7 m MSL) used as a surrogate for Secchi depth (as is done in Chesapeake Bay) converts to an attenuation coefficient of 0.21 m^{-1} using the above equation. Finding a strong correlation between Secchi depth and the lower limit of eelgrass would be very useful in managing water quality and eelgrass health in Puget Sound. Knowing this relationship would allow managers to establish a Secchi depth that is "protective" of eelgrass health.

At present, Secchi depth data are collected monthly by the Washington State Department of Ecology, but their sites are generally too distant from eelgrass meadows to be directly useful. There is likely a difference in water clarity caused by nearshore plankton and suspended particulates that would make conditions over the meadows differ from those in deeper offshore areas. Our recommendation would be to establish new monitoring sites closer to shore in areas where eelgrass is abundant. We further recommend that measurements be taken more often (e.g., weekly) during spring and summer at these sites.

We suspect that patchiness of the meadows might be related to a variety of factors, but that *Ulva* blooms are likely responsible for some of the fragmentation. Thom and Albright (1990) showed that low nutrients limit seaweed production in nearshore areas in Puget Sound. This suggests that nearshore areas are susceptible to large increases in seaweed biomass caused by increased nutrient loading from the land. Data show that nutrients are extremely high from small streams entering the beaches where *Ulva* problems have been observed (Thom et al. 1988; Thom and Albright 1990). The eelgrass patchiness observed in concordance with *Ulva* biomass might be a first indication of such problems being caused by eutrophication in Puget Sound.

The Chesapeake Bay Estuary program has as a principal goal the restoration of seagrass meadows, and uses eelgrass depth distribution as a key monitoring parameter of water quality (Batiuk et al. 1992; Dennison et al. 1993). Certainly, eelgrass can be used for the same purpose in Puget Sound. Monitoring light attenuation along with the eelgrass lower depth limit, *Ulva* distribution, and degree of fragmentation of meadows would provide a powerful data set. Coupling this with sampling of nutrients in the vicinity of the sites would provide a way to integrate our understanding of the changes taking place in the watershed with the health of Puget Sound ecosystems.

Acknowledgements

We gratefully acknowledge the support and interest of J. Schafer, R. Singer, and M. Ossinger of WSDOT in this work. V. Cullinan of Battelle provided valuable help in the analysis of the data.

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